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The sleep architecture of Australian volunteer firefighters during a multi-day simulated wildfire suppression: Impact of sleep restriction and temperature

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ABSTRACT

Wildland firefighting exposes personnel to combinations of occupational and environmental stressors that include physical activity, heat and sleep restriction. However, the effects of these stressors on sleep have rarely been studied in the laboratory, and direct comparisons to field scenarios remain problematic. The aim of this study was to examine firefighters' sleep during a three-day, four-night simulated wildfire suppression that included sleep restriction and physical activity circuits representative of firefighting wildfire suppression tasks in varied temperatures. Sixty-one volunteer firefighters (37.5 ± 14.5 years of age, mean ± SD) were assigned to one of three conditions: *control* ($n = 25$; 8 h sleep opportunities and 18–20 °C), *awake* ($n = 25$; 4 h sleep opportunities and 18–20 °C) or *awake/hot* ($n = 11$; 4 h sleep opportunities and 33–35 °C during the day and 23–25 °C during the night). Results demonstrated that amounts of N1, N2 and R sleep, TST, SOL and WASO declined, whilst sleep efficiency increased significantly in the *awake* and *awake/hot* conditions compared to the *control* condition. Results also demonstrated that SWS sleep remained relatively stable in the *awake* and *awake/hot* conditions compared to *control* values. Most importantly, no significant differences were found for any of the sleep measures between the *awake* and *awake/hot* conditions. Thus, working in hot daytime temperatures in combination with sleep restriction during the night did not affect patterns of sleep compared to working in temperate conditions in combination with sleep restriction during the night. However, the effects on sleep of high (>25 °C) night-time temperatures with sleep restriction in addition to physical activity remains to be studied.

1. Introduction

Firefighting exposes personnel to combinations of occupational and environmental stressors including sleep restriction (Cater et al., 2007), long shifts of variable intensity physical activity (Cuddy et al., 2007; Phillips et al., 2012), and environmental extremes (Aisbett et al., 2012). Australian wild fires are known for hot temperatures (>45 °C) (Cheney, 1976), and require firefighters to work extended periods (up to 16 h per shift) (Cater et al., 2007; Phillips et al., 2012) in deployments that can last for days to weeks (Hunter and Authority, 2003; Rodriguez-Marroyo et al., 2012). As a result, cumulative sleep loss can occur, with firefighters reporting on average 3–6 h sleep per night during multi-day fire deployments (Cater et al., 2007; Gaskill and Ruby, 2004). Inadequate sleep has implications for performance and places individuals at increased risk of error and incident (Åkerstedt and Wright, 2009). Although data on Australian firefighters' sleep patterns are sparse, laboratory and military studies focusing on the individual and combined effects on sleep architecture of physical activity, sleep restriction and/or ambient temperatures provides some insight.

Laboratory studies on the effects of exercise on sleep reveal consistent increases in slow wave sleep (SWS) (Horne and Porter, 1975; Horne and Staff, 1983) and in some cases, associated reductions in rapid eye movement (REM) sleep (Horne and Moore, 1985) if exercise is conducted late in the afternoon and without a sufficient daytime recovery period. The effects of sleep restriction on sleep architecture are also well established, with declines in amounts of

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stage 1, 2, and REM sleep, and a conservation of SWS from sleep doses of 3–6 h per night for 7–14 consecutive days (Belenky et al., 2003; Van Dongen et al., 2003). However, the effects of varying ambient temperatures on sleep patterns are less clear.

Research using temperatures between 21 and 37 °C (Haskell et al., 1981) demonstrated that cold, rather than warm temperatures were generally more disruptive to sleep. Specifically, increases in stage 1 sleep and decreases in stage 2 and REM sleep were reported with 21 °C the most disruptive temperature. In contrast, no significant effects on the total duration of REM sleep or latency were reported during two consecutive nights sleep at temperatures of 13 °C, 16 °C, 19 °C, 22 °C, or 25 °C (Muzet et al., 1983). The effects on sleep during sleep restriction in cool and warm temperatures have also been examined.

Sleep restriction to 4 h for four nights at 20 or 35 °C was associated with decreased amounts of stage 1 sleep and wake after sleep onset (WASO) (Bach et al., 1994). Duration of stage 4 sleep increased over nights of sleep restriction at 20 °C but not 35 °C. Similar military research combining the effects of 4 h sleep restriction for 6 nights with an initial 90 h total sleep deprivation (TSD) period, during a tactical defence exercise in cold winter temperatures, revealed stage 2 sleep decreased whilst all other stages remained constant (Haslam, 1982).

Laboratory and field studies provide insight into the effects on sleep architecture of single or dual stressor combinations of physical activity, sleep restriction, and/or ambient temperatures however the combination of all three has not been studied in the laboratory. Further, where combinations of stressors (i.e., physical activity, sleep restriction and environmental extremes) are similar to that of firefighting, such as in military operations, direct comparisons are limited because such studies typically include periods of TSD at the beginning of experimental trials, in addition to limited control of extraneous variables such as fluctuations in natural weather conditions (Haslam, 1982; Lieberman et al., 2005). The aim of this study was to determine whether changes in sleep architecture from sleep restriction in combination with heat and physical activity are significantly different from those of sleep restriction and physical activity alone, and if these conditions differ from full sleep opportunities during a multi-day simulated wildfire suppression.

2. Methods

2.1. Participants

Participants were active volunteers recruited from the South Australian Country Fire Service, Country Fire Authority (Victoria), Tasmania Fire Service, New South Wales National Parks and Wildlife Service, and Australian Capital Territory Fire and Rescue. In groups of up to five, participants took part in a multi-day simulated wildfire suppression. Participants were assigned to one of three conditions. The *control* condition consisted of 25 participants (3 females (f)), 22 males (m) (mean = 36.7 y, SD = 15.9 y) with a mean BMI of 27.0 kg/m^2 (SD = 4.8 kg/m^2). The *awake* condition consisted of 25 participants (5 f, 20 m) (mean = 38.5 y, SD = 13.2 y) with a BMI of 29.2 kg/m^2 (SD = 4.9 kg/m^2). The *awake/hot* condition consisted of 11 participants (1 f, 10 m) (mean = 37.5 y, SD = 15.6 y) with a BMI of 26.7 kg/m^2 (SD = 4.6 kg/m^2). Power analyses indicated that a total sample size of 75 participants (across three groups) would be required ($\alpha = 0.05$, $1 - \beta = 0.80$), using an estimated effect size of $f = 0.16$ from previous research investigating changes in REM sleep and SWS with ambient temperature changes of 3 °C (Muzet et al., 1983, 1984). However, due to operational time constraints only 11/25 participants could be collected for the *awake/hot* group resulting in a total sample of 61 participants. This yielded an achieved study power of 0.71. Ethics approval was obtained from the CQUniversity and Deakin University Human Research Ethics Committees.

2.2. Procedure

The three-day, four-night multi-day simulated wildfire suppression consisted of a baseline night with an 8 h sleep opportunity (time in bed (TIB) 22:30–06:30 h), followed by two experimental nights with either 8 h or 4 h sleep opportunities (TIB 22:00–06:00 h or 02:00–06:00 h) for the *control* or *awake* and *awake/hot* conditions, respectively. The fourth night was a recovery sleep with all conditions provided with an 8 h sleep opportunity (TIB 22:00–06:00 h). For the *control* and *awake* conditions, day- and night-time temperatures remained between 18 and 20 °C throughout the protocol. From 11:30 h on experimental day one, temperature in the *awake/hot* condition was set to 33–35 °C during the day (06:00–18:00 h), and 23–25 °C during the two experimental nights and recovery (18:00–06:00 h). Temperature was monitored using a wireless temperature and humidity logger (HOBO ZW_003, One Temp Pty Ltd, Australia), data receiver (HOBO ZW_RCVR, One Temp Pty Ltd, Australia), and associated software (HOBO Pro Software, One Temp Pty Ltd, Australia). During the simulated dayshift firefighters performed physical-cognitive test circuits, three to five per day. Each 2 h circuit consisted of 55 min of physical work involving wildland firefighter suppression tasks (for a detailed methodology and the effects of sleep restriction on physical task performance the reader is referred to Vincent et al., 2015), 20–25 min of physiological testing (for a detailed methodology and the effects of heat on physiology and work performance the reader is referred to Larsen et al., 2015) and 20–25 min of cognitive testing (reported elsewhere), followed by a 15–20 min rest period.

2.3. Activity monitors

Actiwatch-64 (Mini-Mitter Philips Respironics, Bend, OR) or Actical Z-series (Mini-Mitter Philips Respironics, Inc.) devices were worn on the non-dominant wrist, prior to and during the experiment. Both activity monitors contain an omnidirectional piezoelectric accelerometer sampling movement at 32 Hz. Data collected with the Actical and Actiwatch (Mini Mitter Co., Inc., Bend, OR) correlated strongly with activity energy expenditure (AEE) and physical activity ratio (PAR) (Puyau et al., 2004) and the outputs from both accelerometers were also highly correlated ($r = 0.93$). As such, both activity monitors provide valid measures of AEE and PAR and can be used to discriminate sedentary, light, moderate and vigorous levels of physical activity.

2.4. Polysomnography and sleeping conditions

Sleep was recorded using the Siesta Portable electroencephalography (EEG) system (Compumedics, Melbourne, Victoria, Australia). A standard montage of electrodes was applied; two channels of EEG (C4-M1, C3-M2); left and right electro-oculograms (left outer canthus, right outer canthus); and two channels of chin electromyography. One and a half hours prior to bedtime each participant had polysomnography Grass™ gold-cup electrodes (Astro-Med, Inc., West Warwick, RI) applied to their face and scalp. All sleep records were blinded and analyzed by a sleep technician in 30 second epochs in accordance with standard criteria (Iber et al., 2007). Participants slept in individual beds located in a single room. Signals from each portable siesta transmitted wirelessly to designated participant laptops located in a separate room monitored overnight by a sleep technician. Ten minutes prior to scheduled bedtimes all sleep and monitoring equipment was placed in position and participants made themselves comfortable prior to lights

Table 1
Results of mixed-effect ANOVAs with physical activity (co-variate), condition and night as fixed terms and participant as a random effect on measures of sleep architecture and quantity.

	Physical activity			Condition			Night			Condition by night		
	F	*df*	*P*	*F*	*df*	*P*	*F*	*df*	*P*	*F*	*df*	*P*
N1 (min)	1.78	1150	.184	3.21	2.60	.047	12.42	3165	<.001	2.36	6157	.033
N2 (min)	1.56	1163	.213	15.19	2.60	<.001	80.38	3164	<.001	23.80	6155	<.001
N3 (min)	1.95	1211	.164	0.31	2.67	.732	10.96	3158	<.001	4.45	6152	<.001
R (min)	1.24	1142	.268	12.63	2.62	<.001	30.13	3166	<.001	14.39	6158	<.001
TST (h)	3.67	1128	.057	42.59	2.58	<.001	110.06	3165	<.001	40.75	6157	<.001
SOL (min)	4.48	1119	.036	4.39	2.60	.017	25.37	3168	<.001	2.04	6161	.064
WASO (min)	2.28	1176	.133	7.39	2.64	.001	25.19	3165	<.001	3.18	6157	.006
Efficiency (%)	1.78	1150	.184	3.21	2.60	.047	12.42	3165	<.001	2.36	6157	.033

out. Participants were provided with an electronic pager should they need assistance throughout the night and were awoken in the morning at the scheduled times with assistance from researchers to remove the monitoring equipment. For each sleep opportunity participants were provided with camping stretchers, inflatable mattresses, and sleeping bags with accompanying pillows and linen to simulate fireground conditions.

2.5. Measures and statistical analyses

Physical activity was measured by averaging the activity count for each 60 second epoch over the 16 h (06:00–22:00 h) period preceding each sleep episode. To assess differences in physical activity a preliminary mixed model analysis of variance was conducted with 2 fixed factors of condition (3 levels – *control*, *awake*, and *awake/hot*) and night (4 levels – baseline, experimental night 1, experimental night 2 and recovery) and a random factor of participants ($n = 61$). Results revealed significant differences in physical activity between conditions over nights (see Section 3.1). Since physical activity changed differentially across conditions, it was specified as a covariate in the models for sleep parameters. Models were run without, then with the covariate with optimal model fit for each sleep variable assessed by comparing Akaike weights between candidate models (Burnham and Anderson, 2002). The denominator degree freedoms for *F* statistics were computed using Satterthwaite approximation method.

For each sleep period, the following dependent variables were calculated: light sleep (i.e., time spent in stage N1 or stage N2 sleep; min), deep sleep (i.e., time spent in stage N3 sleep; min), REM sleep (time spent in stage R sleep; min), total sleep time (TST) (h), sleep onset latency (SOL) (min), WASO (min), and sleep efficiency (i.e., total sleep time/time in bed × 100; %). To assess the main effects of condition and night and the interaction effect of condition by night on sleep dependent variables, data were analyzed using a mixed model analysis of variance with 2 fixed factors of condition (3 levels) and night (4 levels) and a random factor of participants ($n = 61$) with physical activity as a co-variate. All statistical analyses were conducted using SPSS 20.0.

3. Results

3.1. Physical activity

Significant main effects on physical activity were found for condition ($F_{2,71} = 4.37$, $P < .05$) and night ($F_{3,174} = 23.99$, $P < .001$). There was also a significant interaction effect of condition by night on physical activity ($F_{6,174} = 2.76$, $P = .01$). Post-hocs revealed significantly higher physical activity in the *awake* condition compared to the *control* and *awake/hot* conditions, on experimental day 2/experimental night 2 ($P < .01$ and $P = .01$, respectively) and experimental day 3/recovery night ($P < .01$ and $P = .01$, respectively).

3.2. Sleep architecture and quantity

Physical activity was not a significant covariate in any of the models and did not change the effects of the experimental manipulation on any sleep parameters with the exception of SOL (Table 1). There were significant main effects of condition on every sleep measure except N3 (Table 1). There were also significant main effects of night on all sleep measures, and interaction effects of condition by night for all sleep variables except SOL (Table 1). Fig. 1 shows sleep architecture/patterns for each of the stages of sleep in minutes. Stage N1 decreased significantly by experimental night 2, whilst N2 and R sleep significantly decreased over experimental nights 1 and 2, in both the *awake* and *awake/hot* conditions compared to the *control* condition (Fig. 1). N3 sleep remained relatively stable over nights in both the *awake* and *awake/hot* conditions with no significant differences compared to the *control* condition, except for on experimental night one between the *control* and *awake* conditions (Fig. 1).

Fig. 2 shows measures of sleep quantity. TST and WASO significantly decreased over experimental nights 1 and 2 in both the *awake* and *awake/hot* conditions compared to *control* and WASO was still significantly shorter by recovery in the *awake* condition compared to the *control* (Fig. 2). SOL was significantly shorter, whilst sleep efficiency was significantly longer, in the *awake* and *awake/hot* conditions compared to *control* by experimental night 2, and into recovery for SOL (Fig. 2).

4. Discussion

This study examined the effects on firefighters' sleep of a three-day four-night simulated wildfire suppression. The novel simulation involved sleep restriction or full sleep opportunities and physical activity in thermoneutral and hot temperatures. The findings suggest that there are no differences in sleep architecture or sleep quantity during a 4 h sleep opportunity in either slightly elevated or cool, thermoneutral day and night-time temperatures. There were however, significant differences between both sleep restriction conditions and the 8 h sleep opportunity in thermoneutral temperatures. That is, amounts of stages 1, 2 and REM sleep, TST, SOL and WASO declined, whilst efficiency was higher in the *control* condition compared to the *awake* and *awake/hot* conditions on the second night of sleep restriction. In addition, SWS sleep remained relatively stable over the two consecutive nights of sleep restriction and recovery in the *awake* and *awake/hot* conditions compared to *control* values. The only exception was reduced SWS in the *awake* condition on the first sleep restriction night compared to the *control* condition. These results are consistent with previous seminal studies on chronic sleep restriction demonstrating SWS is relatively conserved whilst stage 1, 2 and REM sleep decline relative to the amount of sleep restriction (Belenky et al., 2003; Van Dongen et al., 2003).

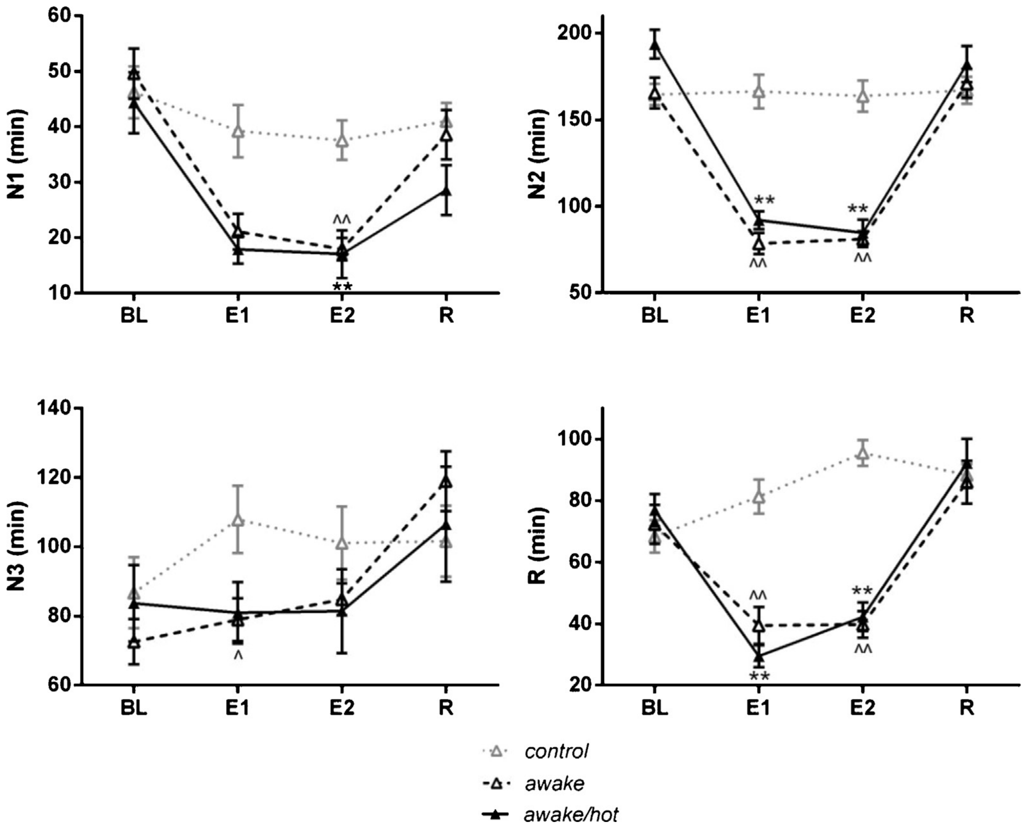

Fig. 1. Sleep architecture. Comparison of sleep stages N1, N2, N3, and R between the three conditions over Baseline (BL), Experimental nights 1 and 2 (E1, E2) and Recovery (R). **($P < .01$) indicates *control* condition values were significantly different from *awake/hot* condition. ^($P < .05$), ^^($P < .01$) indicates *control* condition values were significantly different from *awake* condition. Values expressed as mean ± standard error of the mean (SEM). Error bars represent SEM.

In the current study, performing physical work in high 33–35 °C daytime temperatures did not impact on sleep beyond the effects of sleep restriction alone. This was surprising given a series of studies reporting that high and sustained body heating for 1–2 hours in the afternoon may trigger an increase in SWS regardless of the method of induction (i.e., passive heating (Horne and Staff, 1983), warm temperature baths (Horne and Reid, 1985), or intense exercise (Horne and Porter, 1975)). Similarly, the finding that SWS (stage 3 and stage 4 sleep combined) remained stable during sleep restriction at 18–20 °C contrasts the results of a previous sleep restriction study (Bach et al., 1994) showing that sleep restriction to 4 h for four consecutive nights in 20 °C was associated with a significant increase in stage 4 sleep compared to full 8 h rest opportunities.

Similarly, it would appear that sleep restriction in mild, slightly elevated night-time compared to thermoneutral night-time temperatures, does not adversely affect sleep architecture and quantity. This result is consistent with our previous study reporting no significant differences in sleep patterns between warm (33–35 °C) and thermoneutral (18–20 °C) temperatures with 8 h rest opportunities (Cvirn et al., 2015). Consistent with previous research no significant changes in sleep stages, with the exception of stage 2, have been demonstrated for five consecutive nights sleep at 21 °C compared with five nights at a thermoneutral temperature of 29 °C (Palca et al., 1986). Similarly, no differences in amounts of REM sleep were reported from two nights sleep at temperatures of 13 °C, 16 °C, 19 °C, 22 °C, or 25 °C (Muzet et al., 1983).

However these findings contrast research (Haskell et al., 1981) showing that cold temperatures (defined as 21 °C and 24 °C) were associated with increased amounts of stage 1 sleep, WASO and reduced amounts of stage 2 and REM sleep, compared to a thermoneutral (29 °C) temperature. Although in the present study reduced amounts of stage 2 and REM sleep were seen in both the *awake* and *awake/hot* conditions, the two temperature conditions did not significantly differ in relation to stage 2 or REM sleep. The decrease is therefore more likely due to sleep restriction rather than the experimental temperature manipulation. It should be noted however, that in protocols such as this one and Muzet et al. (1983) where bedding (i.e., sheets and blanket) is provided, the thermoneutral temperature is approximately 19 °C (18–20 °C). However, if participants are required to sleep semi-naked (i.e., shorts; Haskell et al. (1981) and Palca et al. (1986)) the thermoneutral temperature may be higher, around 29 °C. This is due to the finding with adequate bedtime clothing and covering, the microclimate inside a bed will remain near constant at 29 °C, while ambient temperature can be as low as 16 °C (Muzet et al., 1984).

It is possible that night-time temperatures in the range of 18–20 °C or 23–25 °C are too mild to affect night-time sleep. The suggestion that elevated night-time temperatures may be more disruptive to sleep is also consistent with previous research showing increases in WASO and decreases in SWS sleep following ambient temperature increases from 26 °C to 32 °C during the second half of the sleep (Okamoto-Mizuno et al., 2005). Similarly, lower amounts of stage 1 and REM sleep, SWS and TST with increased number and duration of awakenings have been reported with the use of high electric blanket temperatures during the night (Karacan et al., 1978).

Uneven participant numbers between conditions may have contributed to the pre-existing differences at baseline, where significantly increased SOL in the *awake* condition resulted in significantly decreased TST, compared to the *awake*/hot and *control* conditions. This might also explain why there were no significant pre-existing differences on the baseline night for any sleep measures between the *awake* and *control* conditions where participant numbers were

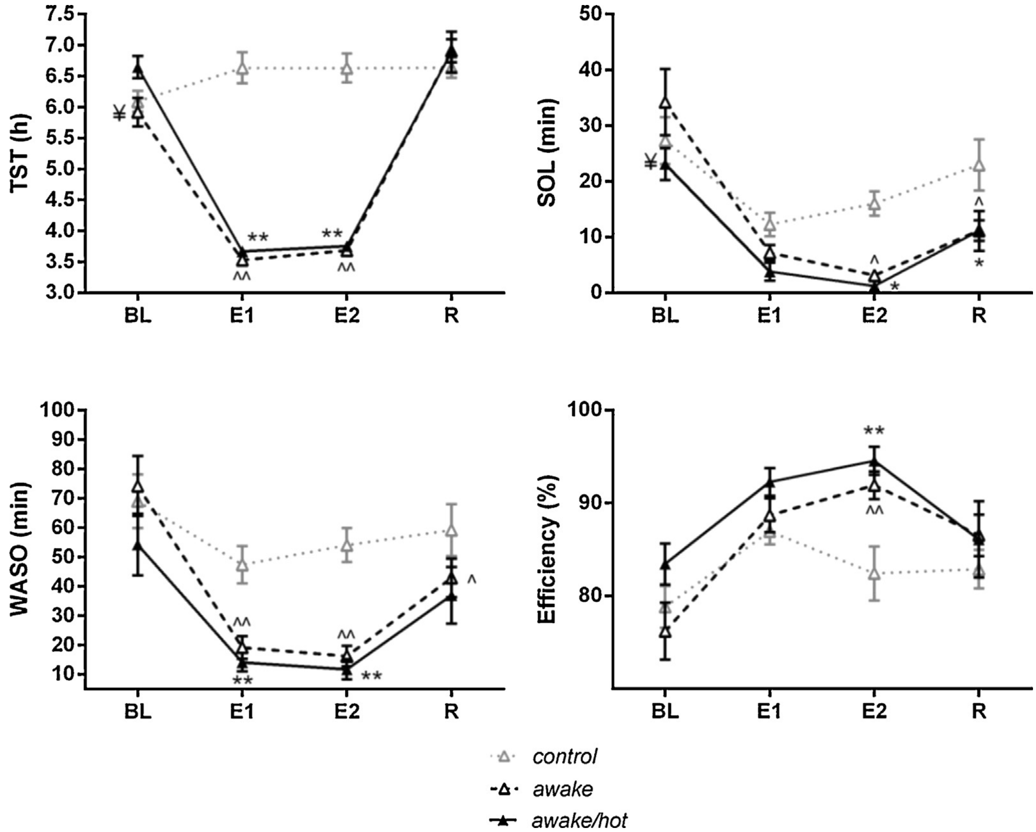

Fig. 2. Sleep quantity. Comparison of TST, SOL, WASO and Efficiency between the three conditions over BL, E1, E2 and R. *($P < .05$), **($P < .01$), indicates *control* condition values were significantly different from *awake* condition. ^($P < .05$), ^^($P < .01$), indicates *control* condition values were significantly different from *awake/hot* condition. ¥ indicates *awake* condition values were significantly different from the *awake/hot* condition ($P < .05$). Values expressed as mean ± SEM.

even. Also as the study was slightly underpowered the findings of no differences between the sleep restriction temperature conditions should be interpreted carefully due to lower participant numbers in the *awake/hot* condition. Additionally, physical activity was a significant covariate for SOL and was associated with a significant decrease in SOL on the second night of sleep restriction and recovery for the *awake* and *awake/hot* conditions compared to *control* values. However, preliminary analyses revealed only the *awake* condition, not the *awake/hot* condition was significantly higher in physical activity compared to the *control* condition over these nights. Hence, the potential for an inverse relationship to exist with increases in physical activity associated with decreases in SOL cannot be substantiated by our findings. However, such an inverse relationship has been reported in a previous meta-analysis on the effects of acute and chronic exercise on sleep (Kubitz et al., 1996).

This study provides the first investigation into the sleep architecture of wildland firefighters during sleep restriction and elevated temperatures. The findings indicate that the effect of sleep restriction is more detrimental to firefighters' sleep than heat. The effect of higher ambient temperatures at night remains to be studied given the increase in this study was mild from 18–20 °C to 23–25 °C. Future research is needed to consider the impact of high night-time ambient temperatures (>25 °C) on sleep architecture in combination with other stressors such as daytime physical activity and sleep restriction.

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